GROUND-LEVEL OZONE:

OCCURRENCE AND TRANSPORT

IN EASTERN NORTH AMERICA

A Report by the

United States-Canada Air Quality Committee

Subcommittee 1:

Program Monitoring and Reporting

March 1999

TABLE OF CONTENTS

1. INTRODUCTION

Foundation for the Transborder Ozone Issue in Eastern North America

Joint Plan of Action for Addressing Transboundary Air Pollution

Joint Workplan

2. AIR QUALITY DATA ANALYSIS

Air Quality Snapshot

Ozone Episodes

Factors that Influence Ozone Concentrations

Air Quality Data Analysis Conclusions

3. AIR QUALITY MODELLING

Model Setup and Episodes

Analysis of Modelling Results

Air Quality Modelling Conclusions

4. POLICY CONCLUSIONS RELEVANT TO THE CONSIDERATION OF AN OZONE ANNEX BY THE AIR QUALITY COMMITTEE

5. REFERENCES

Note: Canadian spelling is used throughout this report.

This is a policy document that provides a summary of information as a basis for decision by the Air Quality Committee.

1. INTRODUCTION

This report presents results of cooperative efforts set in motion in April 1997 to describe ground-level ozone[1] concentrations and transport in the border region of the eastern United States and Canada. It is intended to provide a foundation for a recommendation to governments on the means to jointly address the transboundary ozone issue.

Foundation for the Transborder Ozone Issue in Eastern North America

Ozone has long been recognised as an important health and ecosystem-related air quality concern in the United States and Canada. Recent health and environmental studies in both countries indicate that adverse effects result from ozone exposures at concentrations much lower than previously thought. The United States has recently revised the ozone air quality standards and Canada has a process underway to examine its ozone-related objectives and standards. Both countries have committed to addressing the ozone air quality problem within their own territories. The status of ambient air quality standards and objectives for ozone in Canada and the United States are summarised in Table 1.

TABLE 1. AMBIENT AIR QUALITY OBJECTIVES AND STANDARDS FOR OZONE.

	United States	**Canada**	
Averaging time	National Ambient Air Quality Standards	National Ambient Air Quality Objective	Proposed Canada-wide Standard
1-hour	120 parts per billion (ppb) (std. being replaced by 8-hr)	82 ppb	--
8-hours*	80 ppb (Revised standard)	--	60-70 ppb

*4th highest 8-hours averaged over 3 years

Recognition of the effects of ozone has been accompanied by considerable monitoring and analyses of the spatial pattern of ozone in the two nations. Large-scale summertime smog episodes occur in the eastern half of both countries, with events that transcend political borders. In Canada, exceedences of the current 1-hour 82 ppb (parts per billion) air quality objective are regional in nature, with areas of concern in southern British Columbia in the West, and throughout the Windsor–Québec City Corridor and the Southern Atlantic Region in the East. A similar pattern of regionally elevated ozone occurs in the United States; nationally, a number of areas in California and the Gulf Coast, as well as numerous locations in the eastern portion of the nation exceed the U.S. standards.

The Canadian effort to address ozone exceedences began in 1990 with all governments co-operating to develop the first phase of a management program to reduce precursor emissions of ozone - nitrogen oxides (NOx) and volatile organic compounds (VOC) (CCME, 1990). Since 1990, while the management program has continued to be further refined and implemented, a comprehensive science assessment has defined the nature and extent of the ozone problem in Canada and established the scientific foundation for management options (Multistakeholder, 1997).

[1] The term ground-level ozone, which includes smog-related ozone found in the lower troposphere, is used to make a clear distinction from beneficial stratospheric ozone. Hereafter, the report refers to ground-level or smog ozone simply as ozone.

In the United States, the need to improve upon the effectiveness of ozone implementation programs led to the new classification system, mandatory requirements, and additional mobile source controls embodied in Titles I and II of the 1990 Clean Air Act Amendments. In the process of implementing these requirements, it became clear that expanded regional, as well as local control approaches were essential to meet clean air standards. As a result, 37 eastern states formed the Ozone Transport Assessment Group (OTAG). The OTAG effort produced substantial documentation on the nature of regional ozone transport and alternative strategies (OTAG, 1997). This led directly to promulgation of a major new regional regulatory program to reduce emissions responsible for such transport. The U.S. Environmental Protection Agency (EPA) promulgated this ozone transport rule on October 27, 1998 (EPA, 1998). Since it calls on states to develop implementation plans (SIPs) to address NOx emissions, the rule is known as the NOx SIP call.

Canadian and international studies have reached similar conclusions. In addition to the Air Quality Analysis Workgroup section of the OTAG final report (OTAG, 1997), the Canadian 1996 NOx/VOC Science Assessment reports (Multistakeholder, 1997) have demonstrated that ozone concentrations locally, sub-regionally, and regionally are influenced by background concentrations, locally generated ozone, and transported ozone. The contribution of transported ozone and its precursor emissions occurs over distances of many hundreds of kilometres in the eastern United States and Canada. Recent reports by the Commission on Environmental Cooperation (CEC, 1997) and the International Joint Commission (IJC, 1998) have also highlighted the significance of the transboundary transport of ozone and its precursors to air quality management programs in the United States and Canada.

Joint Plan of Action for Addressing Transboundary Air Pollution

In 1991, Canada and the United States signed the *Air Quality Agreement*, which codified the principle that countries are responsible for the effects of their air pollution on one another. While the *Agreement* initially addressed acid rain, it also confirmed the commitment of the United States and Canada to consult and develop the means to deal with any existing transboundary air pollution problems.

The increasing evidence on regional transport of ozone outlined above led to a recognition that ground-level ozone would be an appropriate issue to consider for the Canada-U.S. *Air Quality Agreement* as early as 1994 (AQC, 1994). Members from both countries met in 1995 to outline a Canada-U.S. Regional Ozone Study Area (ROSA) project. Under this program, the countries initiated regional modelling to evaluate the relative effectiveness of regional controls for ozone pollution in a broad transboundary area in eastern North America. Both counties are also participating in a coordinated program of scientific research and assessment of ozone and particulate matter under NARSTO. This transboundary work occurred in parallel with the domestic OTAG and NOx/VOC Science Assessment activities. Collectively, these endeavours formed the basis of discussions of policy-makers from both countries.

In April 1997, President Clinton and Prime Minister Chretien's meeting reinforced the importance of Canada-U.S. cooperation to protect North American air quality. As part of the President-Prime Minister meeting agenda, U.S. EPA Administrator Carol Browner and

Canadian Minister of the Environment Sergio Marchi signed a “Commitment to Develop a Joint Plan of Action for Addressing Transboundary Air Pollution on April 7, 1997." The commitment was to address jointly shared air pollution problems with ground-level ozone identified as the next priority. In June 1998, EPA Administrator Browner and Canadian Minister of the Environment Christine Stewart signed a report on progress in developing the *Joint Plan of Action.* The Progress Report set targets and schedules for governments in working toward a negotiated ozone annex to the *Air Quality Agreement*. The report identified a strategy of cooperation and joint work, and called for delivery, by April 1999, of a recommendation on negotiation of an ozone annex to the Canadian Minister of the Environment and the U.S. EPA Administrator.

Joint Workplan

The following technical analyses, described in some detail in this document, enable conclusions regarding the transport of ozone in the border regions of the eastern United States and Canada:

- Air quality data analyses using integrated Canadian and U.S. data for the years 1989-1996 to determine how, when, and where transboundary transport of ozone and precursor emissions occurs within the region and the regional extent of elevated 8-hour ozone levels;

- Analyses of factors affecting ozone formation and transport to identify major source regions within the transboundary region; and

- Joint modelling using Canadian and U.S. data and forecasts of planned reduction programs to demonstrate the likely impact of emission control scenarios within the transboundary region.

This document and its conclusions on ozone transport in the border region fulfils the requirement to account, by April 1999, to the Canada-U.S. Air Quality Committee whose mandate is to implement the *Air Quality Agreement.* Further, the conclusions of this report provide support for drafting of possible elements for an ozone annex pursuant to the *Air Quality Agreement*.

2. AIR QUALITY DATA ANALYSIS

Ozone is a photochemical oxidant formed from reactions involving nitrogen oxides (NOx) and volatile organic compounds (VOC) in the presence of sunlight. In order to understand the nature of ozone levels and transboundary flows of ozone and precursor emissions in the border region, this section presents highlights of several existing analyses, assessments, and publications of air quality and meteorology. This work includes the existing and currently ongoing Canadian Multistakeholder NOx/VOC Science Assessment reports (Multistakeholder, 1997) and the OTAG final report (OTAG, 1997). In addition, new analyses that extend these data and analytical techniques into the Canada-U.S. transboundary region were developed for this report and are summarised below (Dann, 1999, Husar et al., 1999; Schichtel and Husar, 1999).

The sections presented here include: a snapshot of current ozone levels, regional maps showing episodic flows in the border region, emissions information, and an overview and analysis of meteorological factors affecting ozone concentrations and transport.

Air Quality Snapshot

The air quality snapshot depicts the regional extent of elevated ozone concentrations in the Canada-U.S. border area based on analysis and maps in an Environment Canada report (Dann, 1999). Data from 100 Canadian sites and 122 U.S. sites for the ozone season (May to September) for the period 1994 to 1996 were used to demonstrate regional patterns in ozone concentrations. Ozone concentrations were computed for running 8-hour periods and maximum 8-hour concentrations by day were determined. The maximum and the fourth highest daily maximum 8-hour ozone values were then computed by site by year.

Figure 1 shows the distribution of fourth highest daily maximum 8-hour ozone concentrations by monitoring site within each region using data for 1994 to 1996. The boxplot figure provides the median, the 95th, 75th, 25th and 5th percentile site ozone concentrations.[2] Figure 2 maps the 4th highest daily maximum 8-hour ozone concentration for the north-eastern portion of North America averaged over the years 1994-1996. Figure 3 provides similar information but uses the average highest daily maximum 8-hour ozone value.

[2] The 95th percentile value shows, for example, that 5% of the monitoring sites in that monitoring region have ozone concentrations that are equal to or higher than that level.

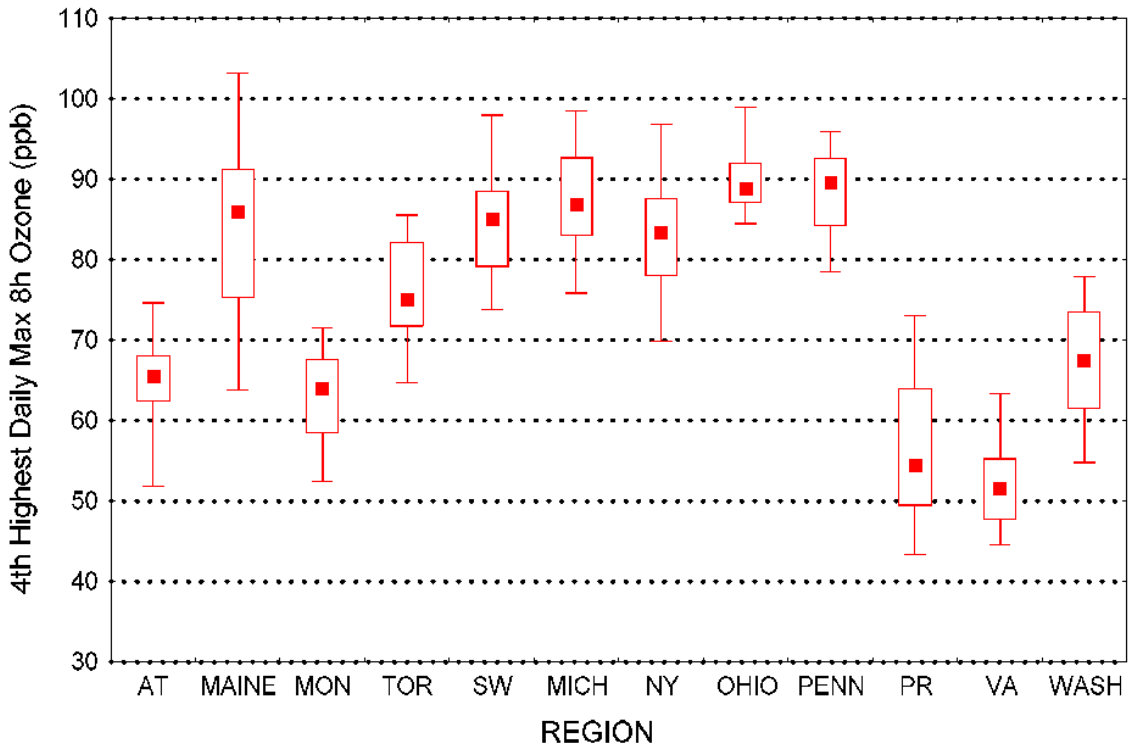


Figure 1. Distribution of 4th Highest Daily 8h Maximum Ozone (ppb) for Regional Sites (1994 to 1996) (Median, 5th, 25th, 75th and 95th Percentiles)[3]. The highest concentrations are recorded at the urban or industrialised sites in the United States (Michigan, New York, Ohio and Pennsylvania) and at the southwestern Ontario (SW) sites. The lowest ozone concentrations are at the Canadian Prairie (Pr) and Vancouver, British Columbia (VA) sites. The state of Maine also records high ozone values that are likely due to transport rather than local generation.

Figures 2 and 3 show large portions of the eastern United States exceeding the 8-hour 85-ppb level with some portions of Ontario also over this threshold. Many regions also exceed the range proposed for the Canada-wide Standard. A significant feature is that ozone concentrations in most of eastern North America, including further east along the coast, into Nova Scotia, and outside the major urban-industrialised areas are well above background concentrations. Maps of ozone episodes are shown in the following section.

[3] Monitoring sites were assigned to the following regions: AT – Canadian Atlantic Provinces, Maine – State of Maine, MON – Montreal Urban Community, TO – Greater Metropolitan Toronto, SW – south-western Ontario, MICH – State of Michigan, NY – State of New York, OHIO – State of Ohio, PENN – State of Pennsylvania, PR – Prairie cities in Manitoba, Saskatchewan, and Alberta, VA – Greater Vancouver Regional District, WASH – State of Washington.

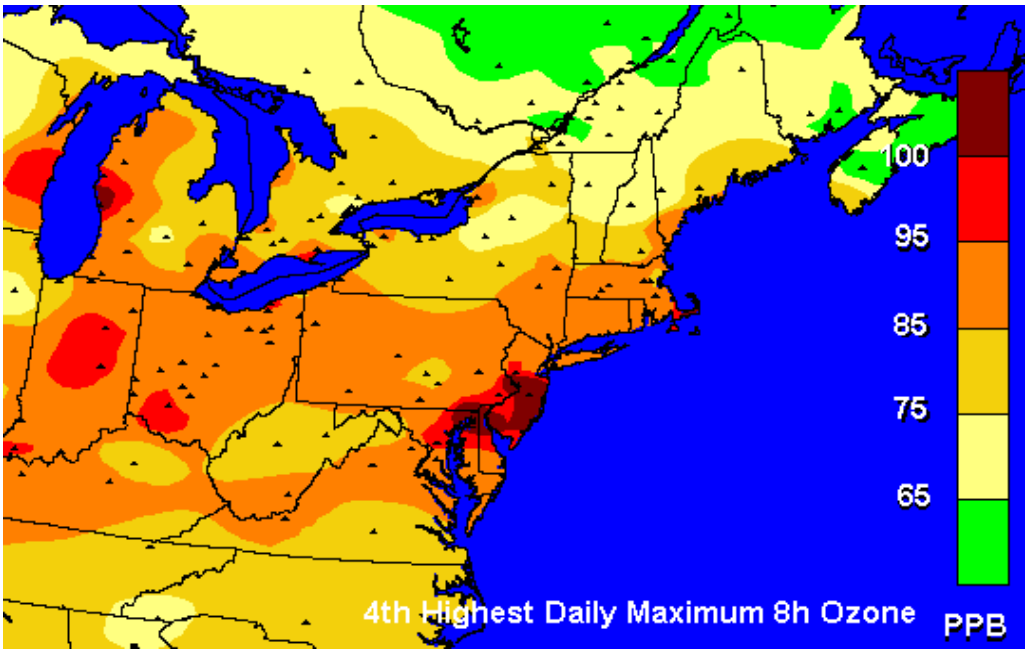


Figure 2. Average of the 4th Highest Daily 8h Maximum Ozone Concentration (ppb) for 1994 to 1996[4].

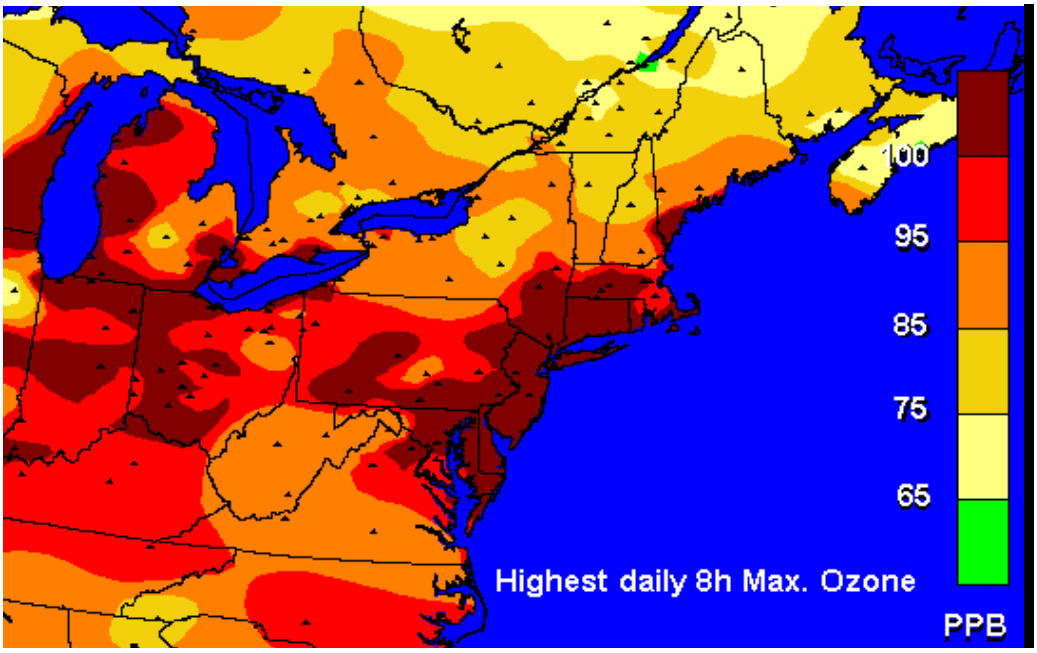


Figure 3. Average of the Highest Daily 8h Maximum Ozone Concentration for 1994 to 1996[4].

[4] Figures 2 and 3 were created using the U.S. EPA sponsored Map Generator program (MCNC-North Carolina Supercomputing Center) and incorporates data from 271 ozone monitoring sites that had at least two years of observations in the 1994-1996 period. The contours were generated using inverse distance weighting interpolation.

Ozone Episodes

Widespread regional episodes are a common feature of eastern North America and have the potential to contribute to exceedences of air quality objectives and standards. To illustrate how a regional episode develops and flows within the region of interest, measured ozone concentration data were compiled from monitoring sites located in eastern United States and eastern Canada for two regional ozone episodes and then mapped. The episode years, 1988 and 1995 were chosen because they show clearly ozone transport within the region of interest over the duration of the episodes. The 1988 episode illustrates ozone transport in both directions across the Canada-U.S. border whereas the 1995 episode illustrates a good example of transport from the United States to Canada. Both episodes were also used in the joint modelling scenarios presented later in this report.

During the summers of 1988 and 1995, ozone-rich plumes were transported across all of eastern North America. Many sites recorded multiple hours and days with ozone concentrations greater than the Canadian and U.S. air quality criteria. The following series of maps (Figures 4, 5 and 6) depict the levels of ozone concentrations in eastern United States and Canada at four progressively later hours in a day during an episode. The maps provide the magnitude and extent of high concentrations while demonstrating movement of ozone over time through the region.

These figures illustrate that essentially all areas of eastern Canada and most areas of the eastern United States experience high concentrations of ozone. Although some areas experience very high 8-hour concentrations, widespread areas experience concentrations ranging from 60-80 ppb and from 80-100 ppb over 8 hours. The following section will discuss what factors contribute to high ozone concentrations locally and regionally.

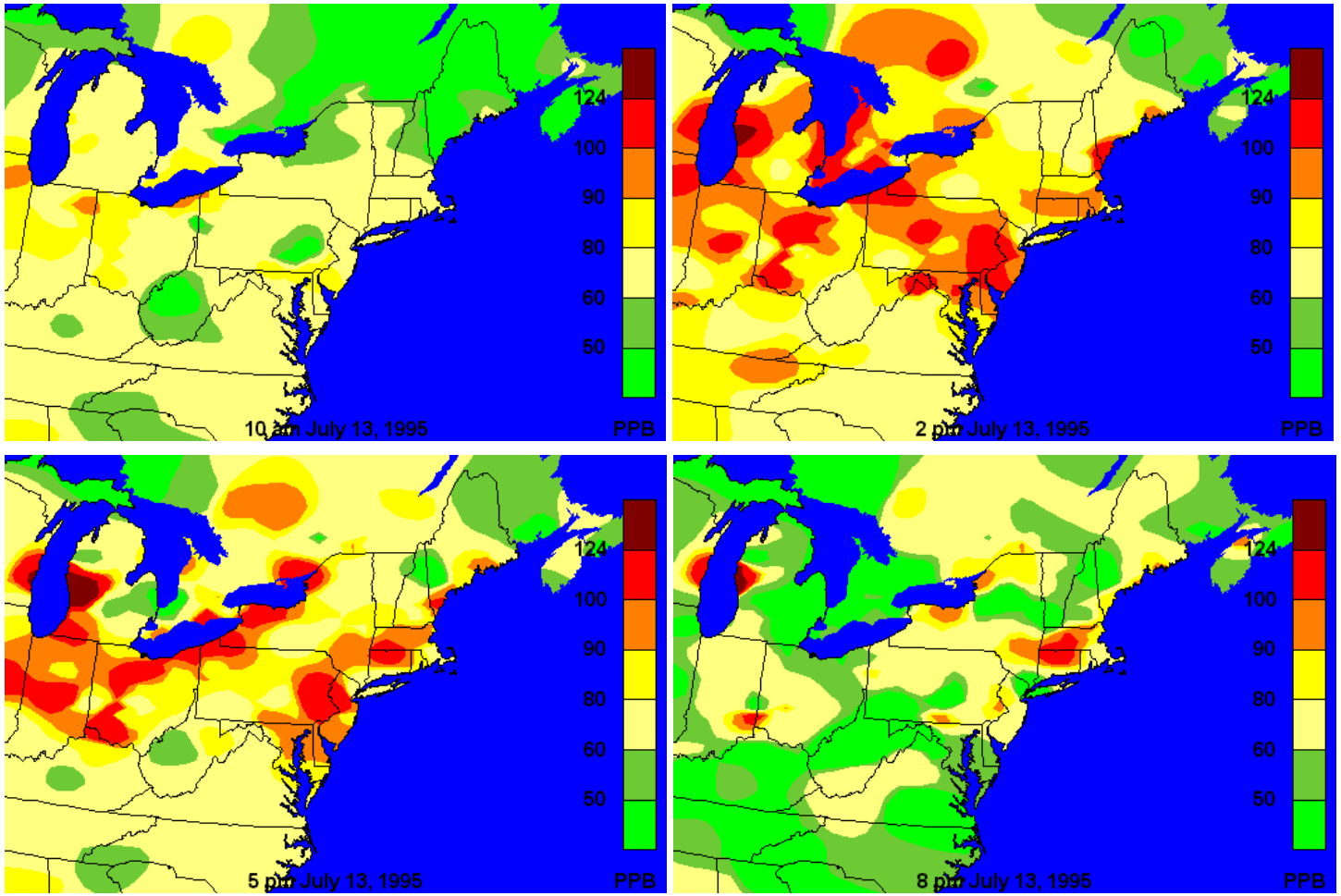


Figure 4. Ozone Transport on July 13, 1995 10AM - 8PM. The first frame shows a regionally uniform pattern of ozone levels. Transport generally followed a north-easterly path, across the heavily industrialised and urbanised area of the U.S. Midwest, then across the Great Lakes (frame 2) into southern Ontario and out to the coast. After picking up local emissions, transport continues west along the St. Lawrence river basin (frame 3) and finally out to the North Atlantic.

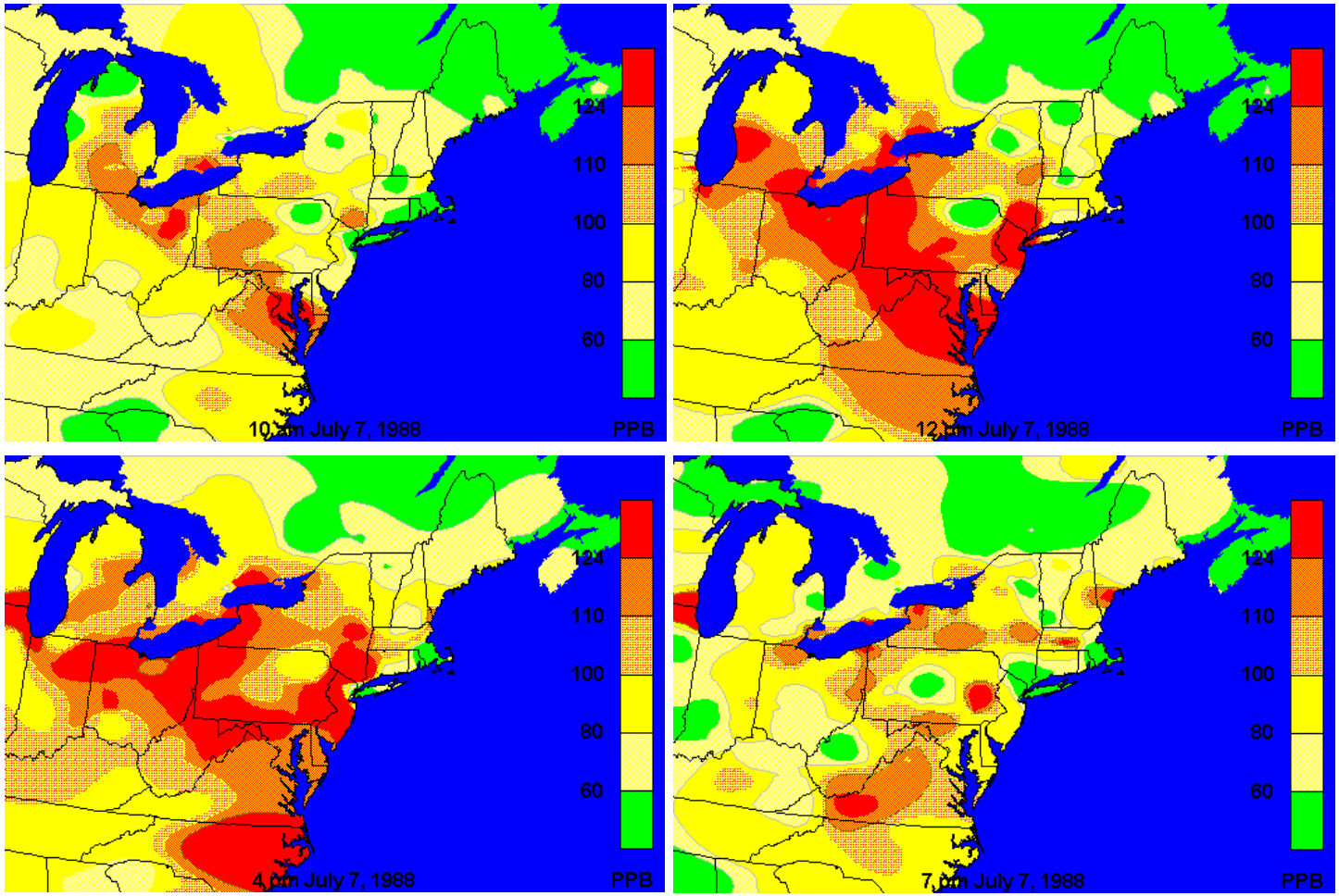


Figure 5. Ozone Transport on July 7 1988, 10AM - 7PM. These frames show fewer urban-industrial peaks and an elevated non-urban pattern extending across most of eastern North America. Both characteristics are evidence of regional scale transport.

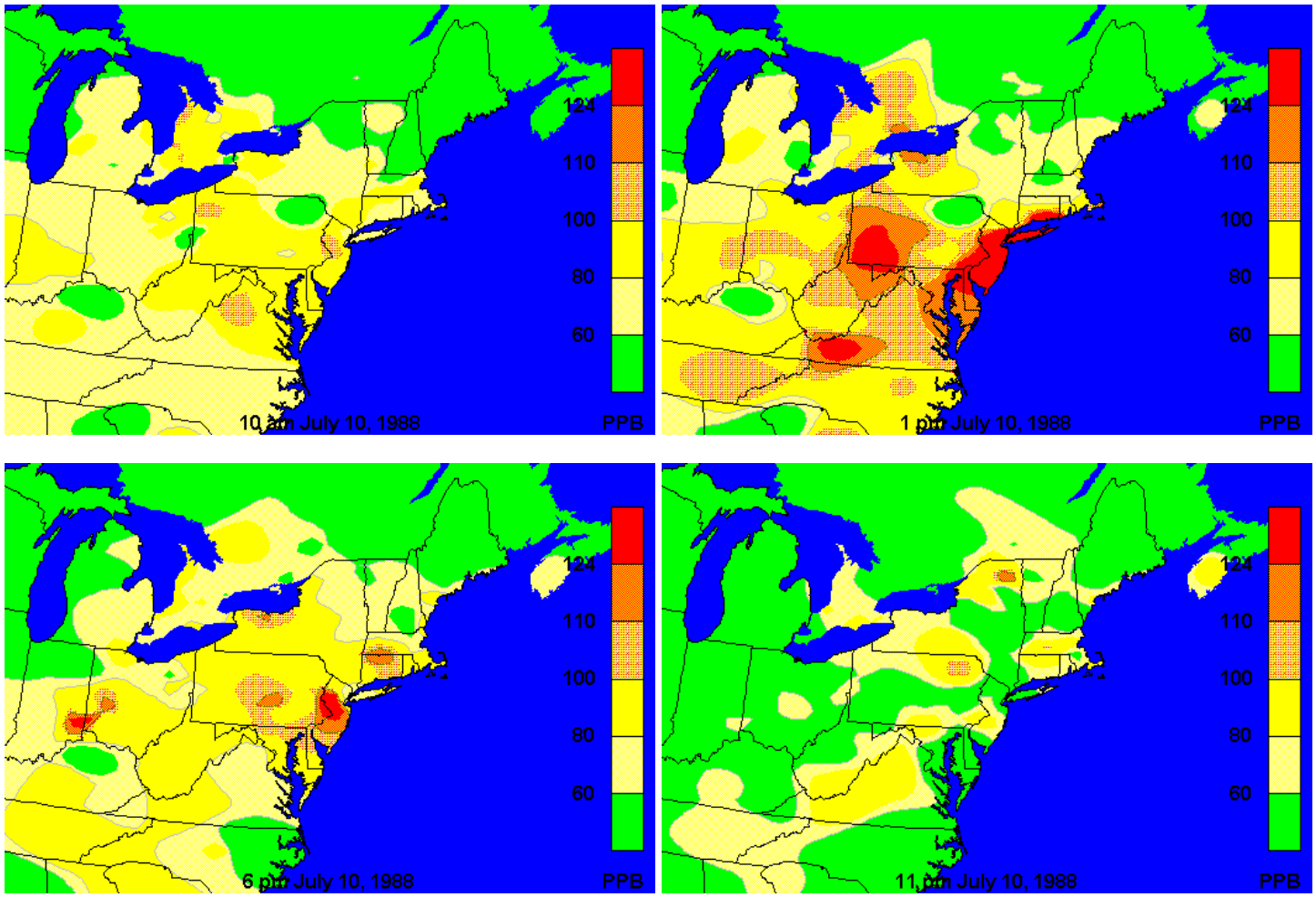


Figure 6. Ozone transport on July 10, 1988, 10AM – 11 PM. Figure 6 shows night time flows into eastern Canada when concentrations greater than 82 ppb occur late in the evening in the southern Atlantic region (frame 4) after high ozone concentrations have moved across the Northeast region (IND, WV, VA, OH, PA, ON) and along the Atlantic seaboard.

Factors that Influence Ozone Concentrations

The direction and spatial extent of transport and the relative contribution of transported ozone and precursors to individual ozone exceedences are highly variable. A number of factors influence site-to site differences in ozone concentrations, including sources of precursor emissions and large-scale and local meteorology. The following information comes from several sources, including the Canada-U.S. Air Quality Agreement 1998 Progress Report and analyses conducted for this report as cited above.

Sources of Ozone Precursors and their Influence on Ozone Formation

As discussed previously, ozone is not emitted directly, but formed in the atmosphere by reactions of "precursors" (NOx and VOCs). Both NOx and VOCs are emitted from a variety of sources. Anthropogenic sources of NOx emissions in the United States are 10 times larger and VOC emissions are 7 times larger in magnitude than in Canada, paralleling the relative population ratio between the two countries.

The relative distribution of major sources categories of NOx and VOC emissions in the U.S. and Canada are somewhat different, as shown in Figures 7 and 8. Although transportation is the largest source of both precursor emissions in both countries, there are some significant differences in source apportionment. For instance, electric utilities in the United States generate 27% of total NOx while contributing only 11% in Canada. Although not shown in these figures, natural emissions also play an important role with respect to summertime emissions of VOCs when emissions from vegetation, for example, have been found to equal or exceed manmade VOC emissions over large regions of eastern North America.

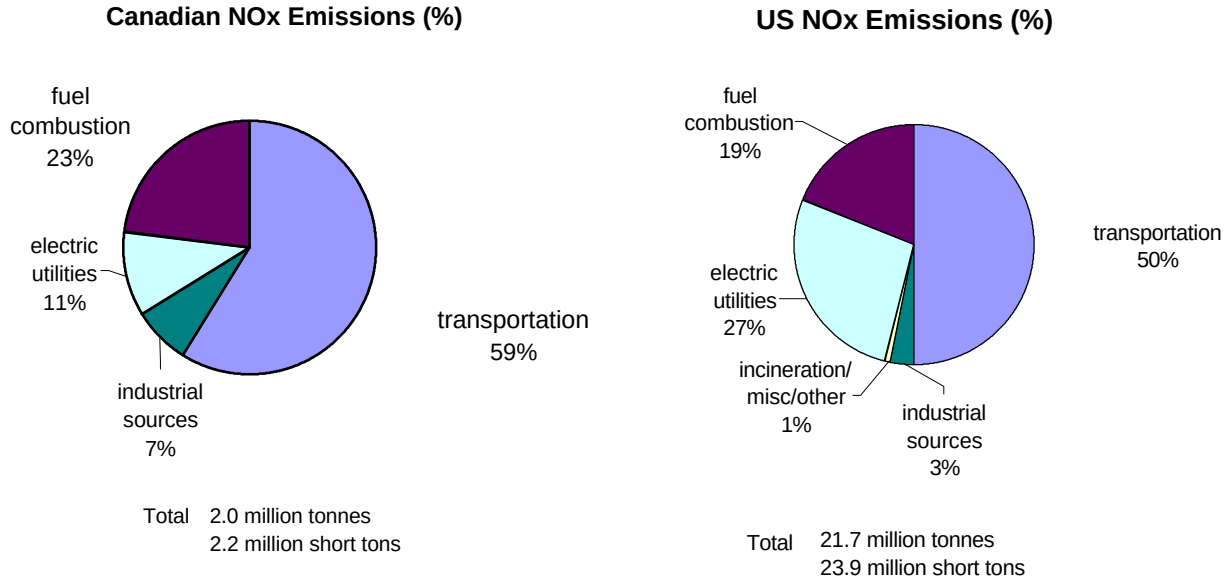


Figure 7. NOx Emissions in Canada and the United States (1995).

Source: Canada-United States Air Quality Agreement 1998 Progress Report, p15.

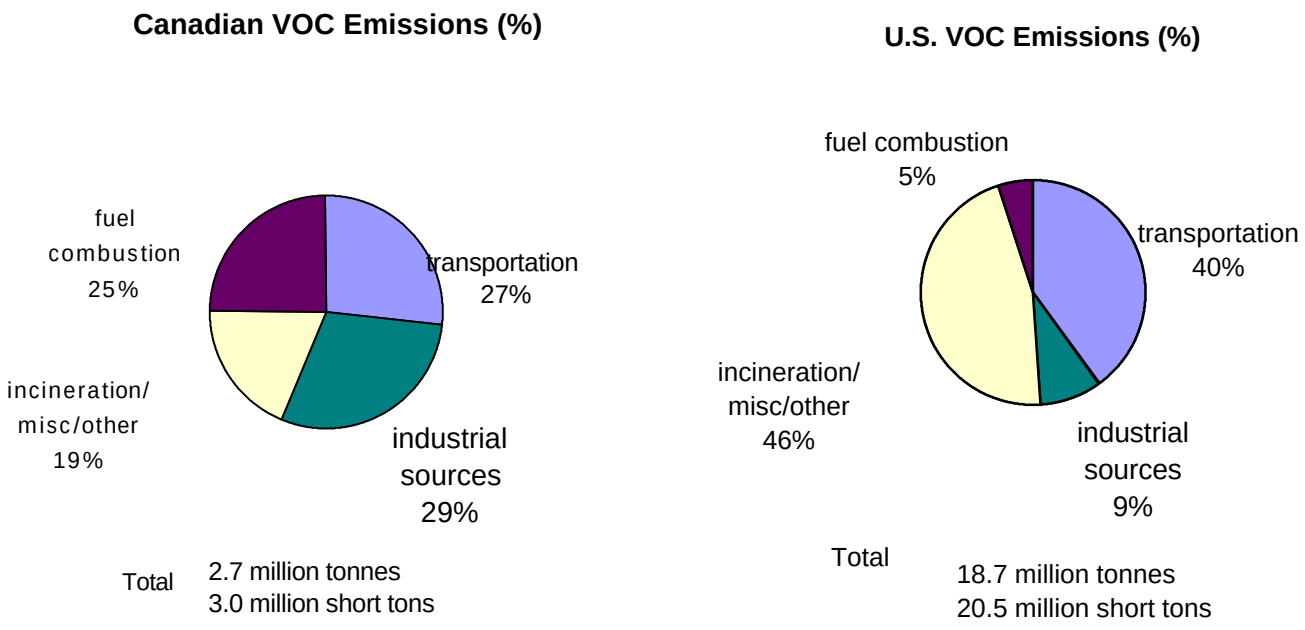


Figure 8. VOC Emissions in Canada and the United States (1995).

Source: Canada-United States Air Quality Agreement 1998 Progress Report, p15.

Although both VOC and NOx emissions contribute to ozone formation, the relative effectiveness of reductions of the two precursors can vary with location and atmospheric conditions. Many publications and reports have examined the impacts of reducing VOCs versus NOx in different urban and regional domains of the United States and Canada (NRC, 1991; OTAG, 1997; Multistakeholder, 1997; CEC, 1997). While the specifics of this situation can be quite complex, the following general conclusions can be reached based on these reports:

1) In urban conditions with relatively low VOC to NOx ratios, anthropogenic VOC reductions can be the most effective strategy for reducing ozone levels; in such conditions, NOx reductions can lead to localised increases in ozone, with decreases in ozone downwind.

2) In conditions with high VOCs relative to NOx, such as downwind of major urban centres, NOx controls may be the most effective strategy for reducing ozone. Due to the day-to-day variability in emission levels, background VOC and NOx concentrations and wind patterns, both NOx and VOC controls may be needed to reduce ozone in particular urban areas.

3) In rural areas of eastern North America, there is an abundance of naturally produced VOCs. In such areas, control of smaller anthropogenic VOC emissions may be ineffective, and NOx controls are an effective control approach.

4) Over a large multi-dimensional region - one that has both urban and rural areas with naturally produced VOCs and anthropogenic NOx emissions transported downwind of urban areas - regional reductions of NOx are the most effective control approach. As shown in this report, the eastern Canada-U.S. border region is such a multi-dimensional region. Therefore, NOx reductions should be the most effective control approach.

The spatial patterns of NOx emission sources in Canada and the United States are shown in Figures 10 and 11. The figures show high NOx emission densities in urban-industrialised areas, although the order of magnitude is different from Canada to the United States.

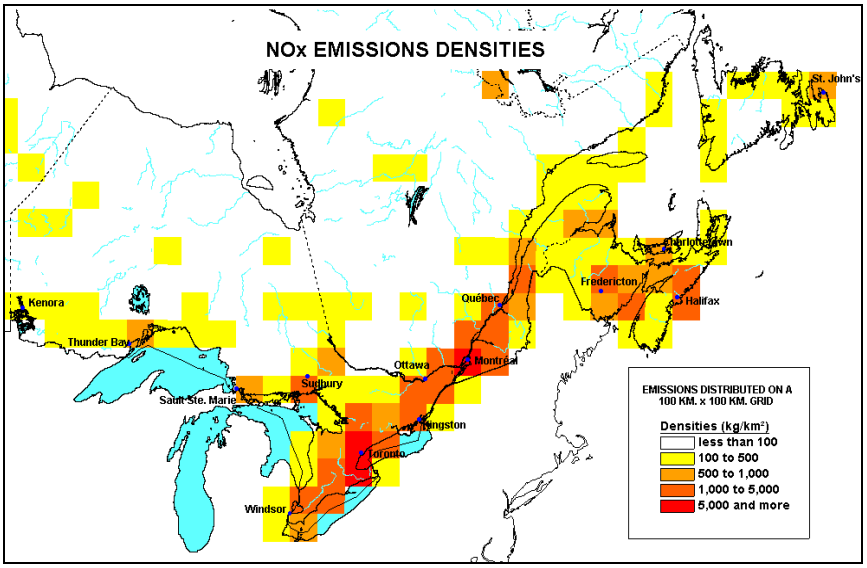


Figure 9. 1995 NOx Emission Densities (in kg/km^2) for Eastern Canada.

Source: Environment Canada Pollution Data Branch.

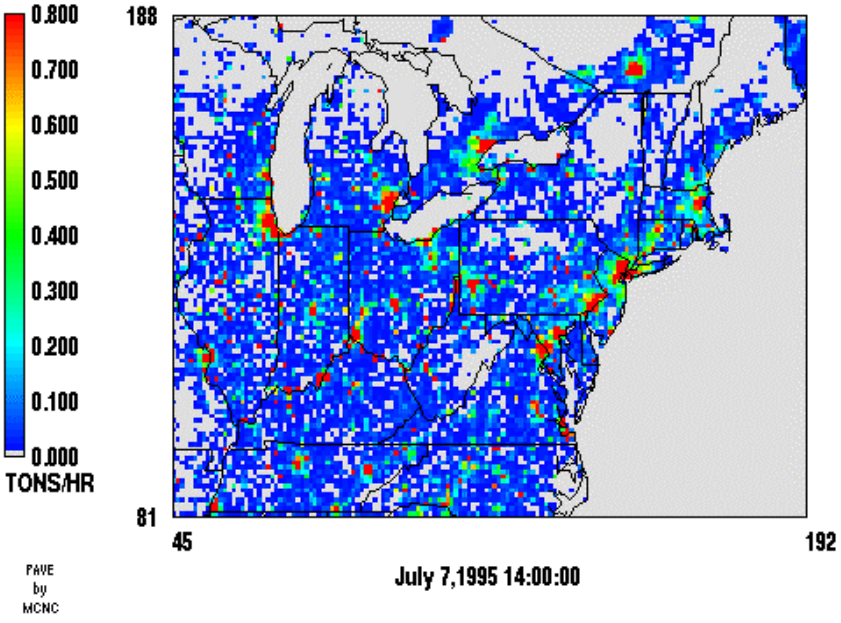


Figure 10. NOx Emission Densities (in tons/hr/grid) in the Eastern United States and Canada. The emissions included on this map for the U.S. reflect the 1995/96 base year emissions that were used in the NOx SIP Call. The emissions for Canada are the 1990 emissions that were used by OTAG.

In the transborder region, the areas of highest emission densities are along the Canada-U.S. border and along the Atlantic coast in the United States. Taken together, these twin corridors of dense population and precursor emissions run from the Southwest to the Northeast, in parallel to weather patterns that frequently occur in the summer. The metropolitan areas along the Canada-U.S. border also have high emission densities of ozone precursors. The following sections present data on transport meteorology, and show the relationship between transport and ozone concentrations within the region.

Ozone as a Function of Wind Speed and Direction

Analysis of ozone a function of wind speed and direction can help provide insight into the relative importance of local and distant sources under varying meteorological conditions. Previous analyses, including those done for OTAG (OTAG, 1997) and for the Canadian Multistakeholder NOx/VOC Science Assessment (Multistakeholder, 1997) indicate that these factors are important influences on the transport of ozone. The series of analyses for the OTAG region has been extended for this report to include Canada to provide more specific insights into transboundary issues (Husar et al., 1999).

In order to analyse the effects of wind speed and direction on ozone concentrations, analysts sorted 11 years of measured ozone concentrations (1989-1996) and averaged for specific wind direction and speed ranges. The average ozone concentration was computed for each wind direction range in 90^{o} increments, starting with 0-90°, i.e. when the wind blew from the North or Northeast. This resulted in four wind directional concentration bins. The average concentrations for each directional bin were further classified by wind speed, ranging between 0-2, 2-4, 4-6, 6-8 metre/second (m/s) increments. Thus, there were four directional and four wind speed bins, yielding a total of 16 concentration bins.

The results of this analysis are presented in maps of average ozone concentration for the four wind directions and three wind speeds - low, medium and high (Figures 11, 12, 13). The detailed results are discussed in a supporting technical paper (Husar et al., 1999).

In summary, average ozone concentration maps at low wind speeds (<3 m/s, Figure 11) show elevated levels of ozone throughout the eastern North American domain. Ozone concentration hot-spots appear over the major metropolitan areas in the United States and the Ohio River Valley but the concentrations are virtually the same regardless of the wind direction. Ozone concentrations in metropolitan areas of Canada are similar to surrounding sites. At intermediate wind speeds (3-6 m/s, Figure 12) the overall concentrations are lower, and the higher ozone concentrations appear to be displaced up to 500 km downwind of the major source areas. At high wind speeds (>6 m/s, Figure 13) most metropolitan source areas do not cause elevated ozone in their own vicinity. Rather, higher concentrations appear in the downwind corners of the eastern North American domain, up to 1000 km from the domain centre.

The ozone concentration pattern at different wind directions and speeds are consistent with an atmospheric ozone lifetime of about one day and a corresponding transport distance of 200, 500 and 800 km at 2, 5, and 8 m/s respectively. Therefore, at low wind speeds, ozone accumulates near precursor emission source areas. Higher wind speeds cause increased dilution of local concentrations and increased transport from one source region to another.

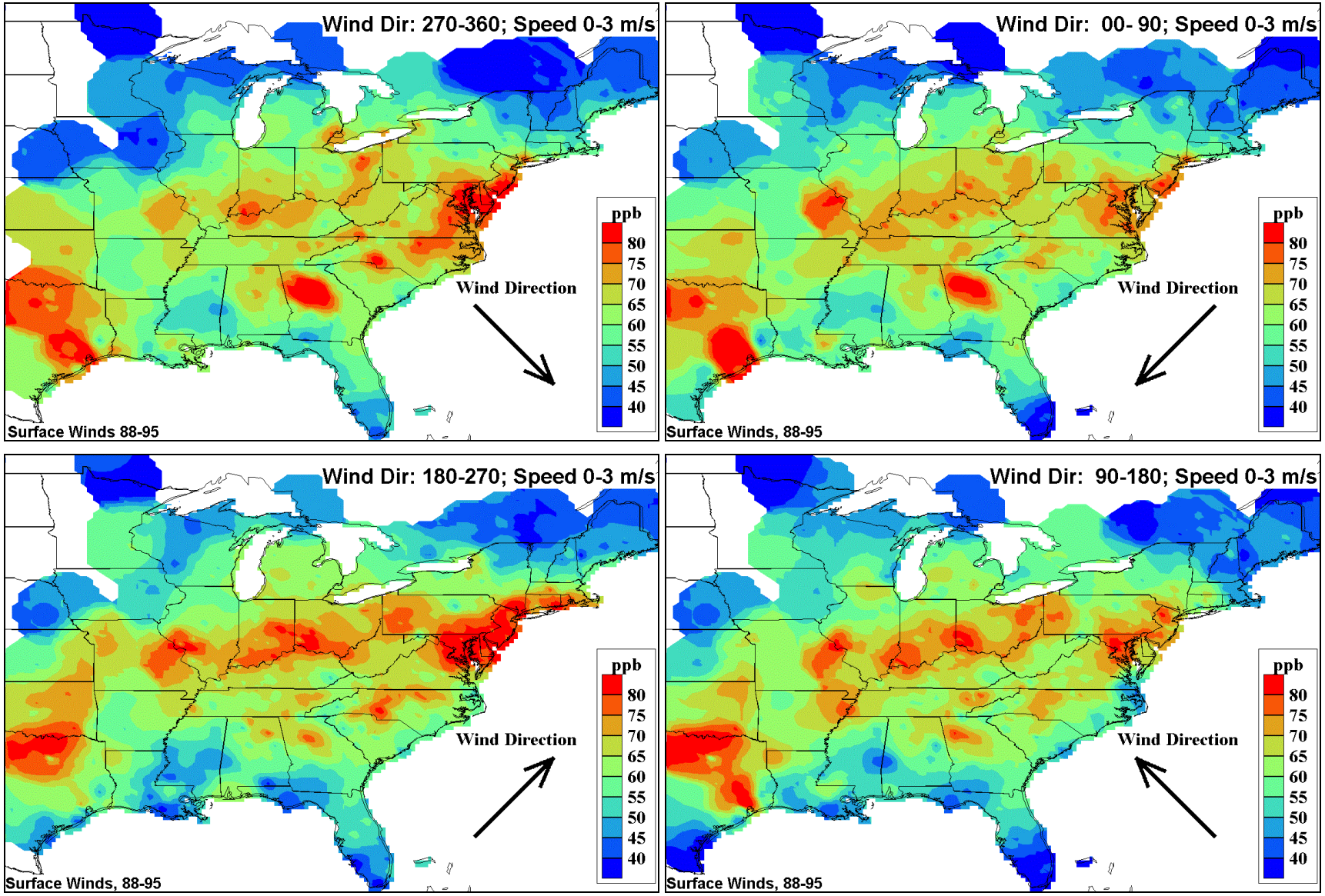


Figure 11. Maps of average ozone concentration at low (<3 m/s) wind speed. a) 270-360 degrees, b) 0-90 degrees, c) 90-180 degrees, d) 180-270 degrees. At low wind speeds, ozone concentrations tend to be somewhat higher just downwind of urban areas. Concentrations tend to be fairly similar, regardless of wind direction. In such cases, local sources likely dominate ozone formation.

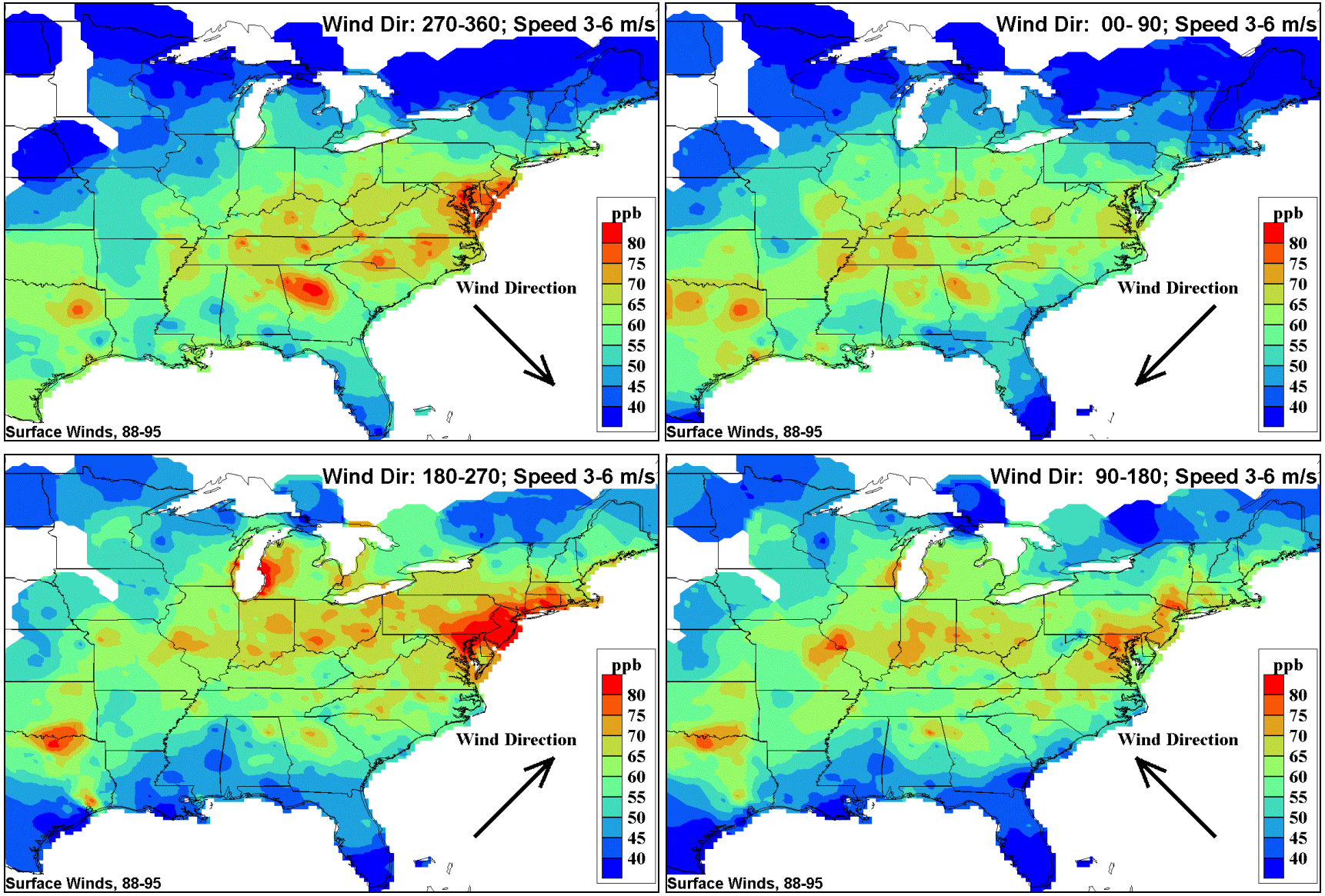


Figure 12. Maps of average ozone concentration at intermediate (3-6 m/s) wind speed. a) 270-360 degrees, b) 0-90 degrees, c) 90-180 degrees, d) 180-270 degrees. At intermediate wind speeds, there are substantial differences between the maps depending on the wind direction. Northerly flows (frames a and b) show low concentrations throughout Canada and the northern United States. Southerly flows result in higher concentrations in the north, especially in the Michigan/Ontario/New York region.

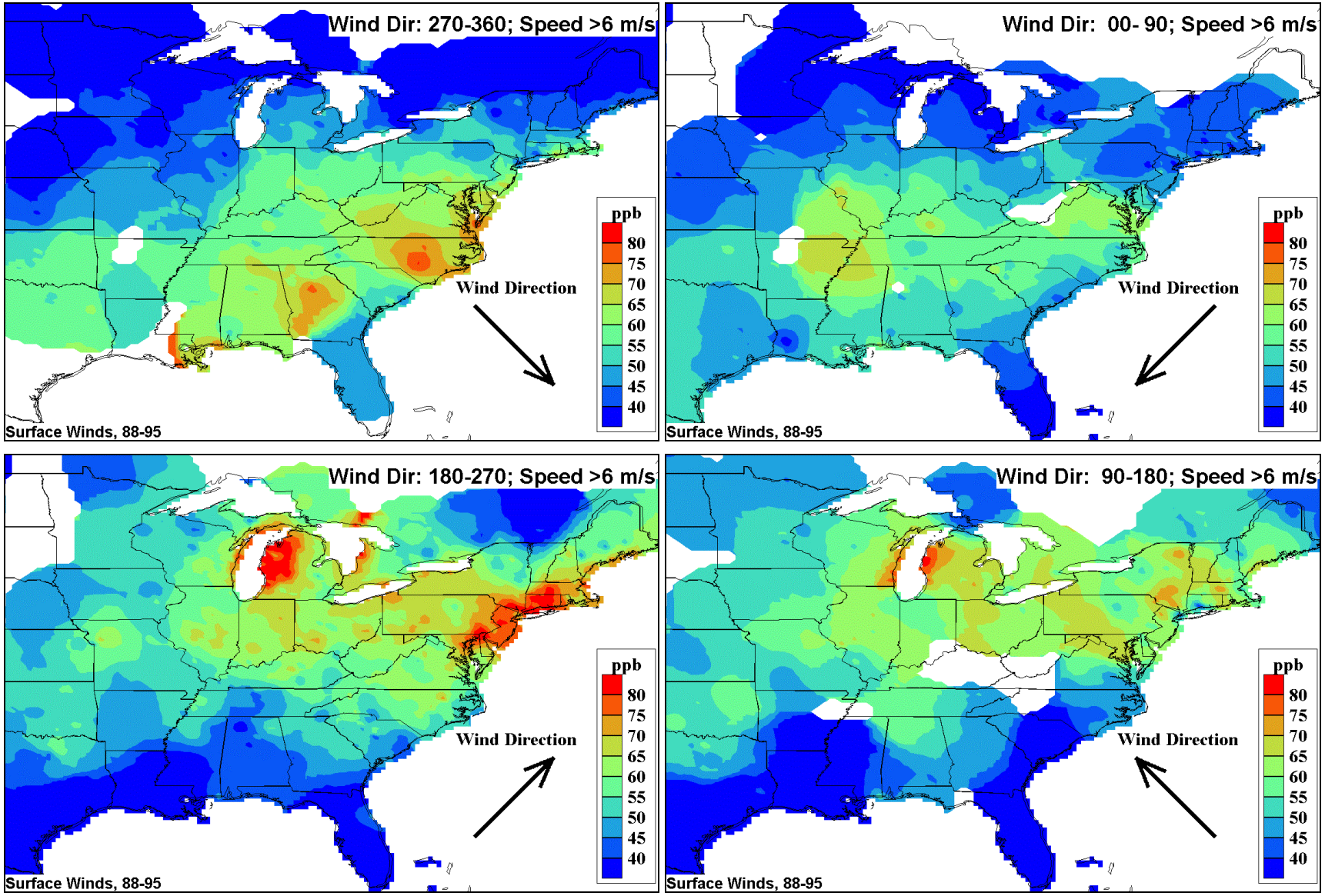
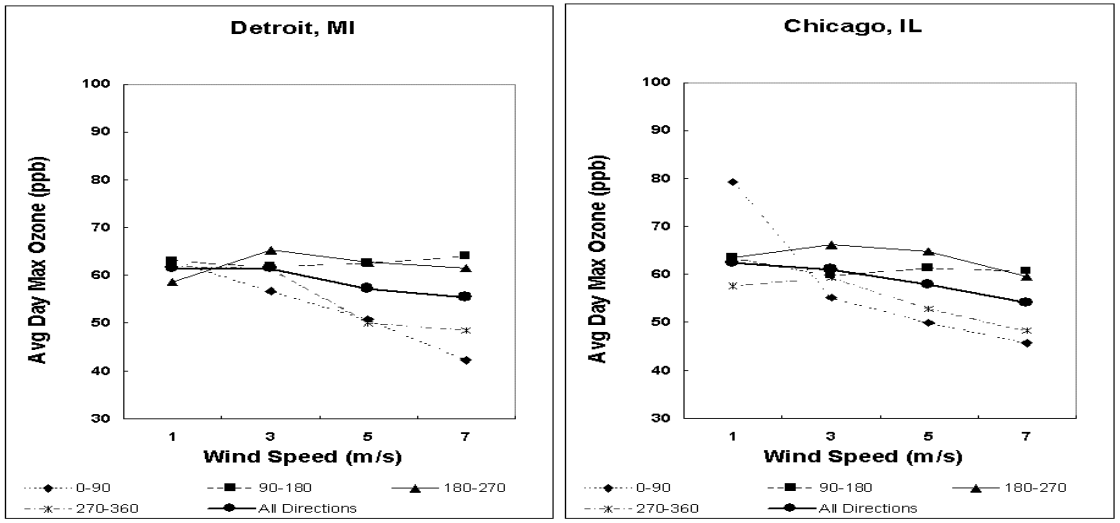


Figure 13. Maps of average ozone concentration at high (>6 m/s) wind speed. a) 270-360 degrees, b) 0-90 degrees, c) 90-180 degrees, d) 180-270 degrees. At high wind speeds, the eastern North American domain appears as a regional domain, although there are still some near-urban areas of elevated ozone.

Graphs of individual urban areas (Detroit, Chicago and Toronto) in the north-central domain show the average ozone concentrations at four characteristic speeds (1,3,5,7 m/s) from wind speed ranges of 0-2, 2-4, 4-6, 6-8 m/s respectively. The data are further stratified by four wind directional quadrants from 0-90 degrees through 270-360 degrees. A fifth line represents wind speed dependence of ozone, regardless of direction.



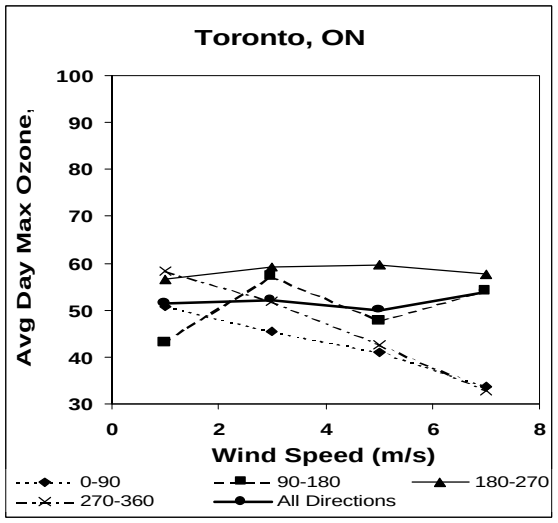


Figure 14. Dependence of ozone concentration on wind speed and direction at different metropolitan areas. The metropolitan areas of Chicago, Detroit and Toronto show a remarkable directionality of the ozone-wind speed dependence. Northerly winds (270-90 degrees) are associated with declining ozone with wind speed. This is interpreted as evidence of substantial local contributions. On the other hand, the wind directions from the centre of the eastern United States are associated with speed-independent ozone levels, implying transported ozone. Taking into account all wind directions, transport is clearly an important component of the ozone problem in each of these areas.

The results for the three urban areas (Figure 14) show remarkable directionality of the ozone-wind speed dependence. For these areas, when the wind blows from the North (270-90 degrees), ozone concentrations decrease with increasing wind speed. This pattern is consistent with locally generated ozone. When the wind blows from the South (90-270 degrees), the graphs show speed-independent ozone concentrations,

indicative of levels dominated by transport.

The following section examines the transport of ozone on days of regionally high and low ozone concentrations.